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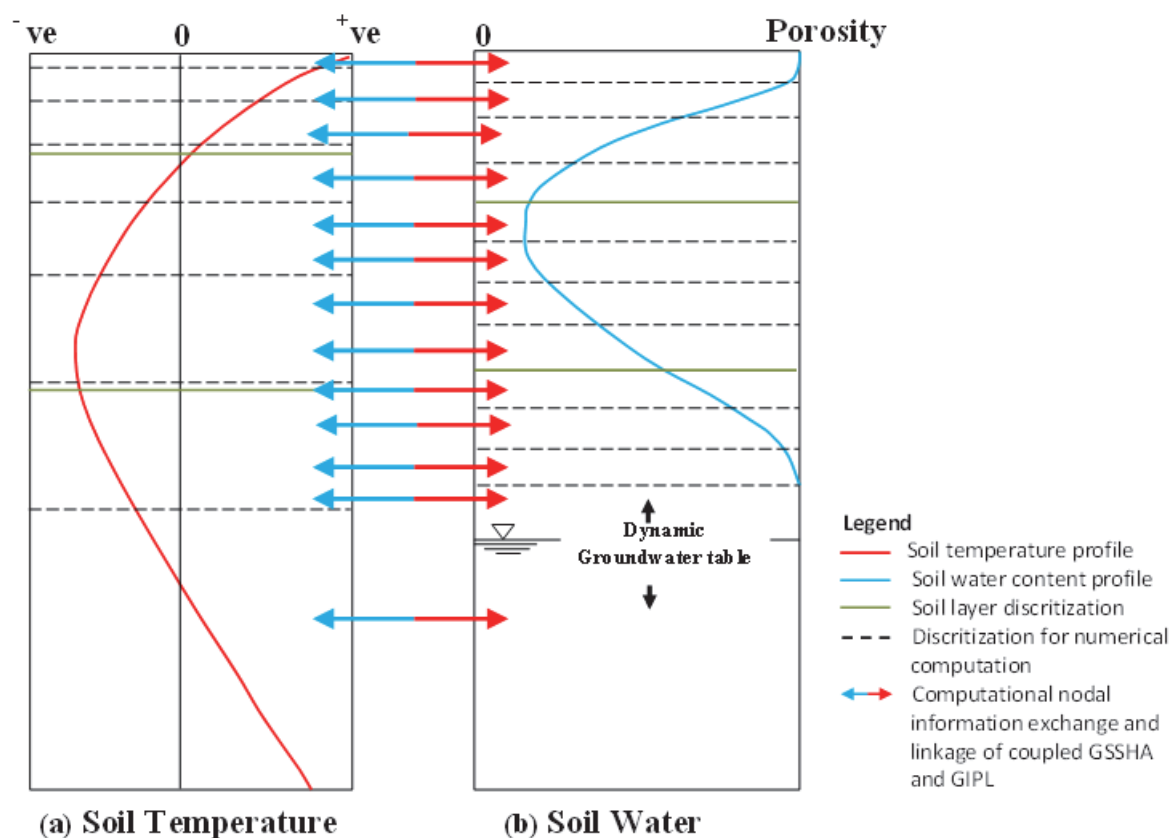
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## **Development of a Coupled Framework for Simulating Interactive Effects of Frozen Soil Hydrological Dynamics in Permafrost Regions**

Nawa Raj Pradhan, Charles W. Downer, Sergei Marchenko,  
Anna Liljedahl, Thomas A. Douglas, and Aaron Byrd

November 2013



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# **Development of a Coupled Framework for Simulating Interactive Effects of Frozen Soil and Hydrological Dynamics in Permafrost Regions**

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## Abstract

Climate warming is expected to degrade permafrost in many regions of the world, including Alaska. Degradation of permafrost has the potential to dramatically affect soil thermal, hydrological, and vegetation regimes. Projections of long-term effects of climate warming on high latitude ecosystems require a coupled representation of soil thermal state and hydrological dynamics. Such a framework was developed to explicitly simulate the soil moisture effects of soil thermal conductivity and heat capacity and its effects on hydrological response. The model is the result of coupling the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model with the Geophysical Institute Permafrost Laboratory (GIPL) model. The GIPL model simulates soil temperature dynamics, the depth of seasonal freezing and thawing, and the permafrost location by numerically solving a one-dimensional nonlinear heat equation with phase change. The GSSHA model is a spatially explicit hydrological model that simulates two dimensional groundwater flow and one-dimensional vadose zone flow. These two models were combined by incorporating the GIPL model into the GSSHA model. The GIPL model is used to compute a soil temperature profile in every two-dimensional GSSHA grid. GSSHA uses this information to adjust hydraulic conductivities for both the vertical unsaturated soil flow and lateral saturated groundwater flow. Test case results indicate that freezing temperatures reduces soil storage capacity thereby producing higher peak discharges and lower base flow.

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## **Preface**

This study was conducted for the Strategic Environmental Research and Development Program (SERDP) under Project Number 11 RC-2110, “Addressing the impacts of Climate Change on US Army Alaska with Decision Support Tools Developed through Field Work and Modeling.

The work was performed by the Hydrologic Systems Branch (HF-H), Flood and Storm Protection Division (HF), US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL). At the time of publication, Dr. Aaron R. Byrd was Chief, CEERD-HF-H; Dr. Ty V. Wamsley was Chief, CEERD-HF; and William Curtis, was the Technical Director for ERDC-CHL. The Acting Deputy Director of ERDC-CHL was Dr. Richard Styles and the Director was José E. Sánchez.

COL Jeffrey Eckstein was the Commander of ERDC, and Dr. Jeffery P. Holland was the Director.

## Unit Conversion Factors

Multiply	By	To Obtain
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
Feet	0.3048	meters
gallons (US liquid)	3.785412 E-03	cubic meters
Inches	0.0254	meters
Knots	0.5144444	meters per second
Microns	1.0 E-06	meters
miles (nautical)	1,852	meters
miles (US statute)	1,609.347	meters
miles per hour	0.44704	meters per second
Mils	0.0254	millimeters
ounces (US fluid)	2.957353 E-05	cubic meters
pints (US liquid)	4.73176 E-04	cubic meters
quarts (US liquid)	9.463529 E-04	cubic meters
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square miles	2.589998 E+06	square meters
square yards	0.8361274	square meters
Yards	0.9144	meters

# 1 Introduction

Future climate change scenarios indicate significant increases in temperature are projected, especially near Earth's poles. This has the potential to significantly impact regions of the world where permafrost currently exist, near the poles where temperatures are projected to increase the most. Changes to permafrost and to the seasonally frozen soil regime have the potential to significantly alter the local hydrology and resulting ecosystem. More generally, the soil-freezing characteristic, a relationship between unfrozen water content and temperature, is relevant for any mass transfer processes in frozen porous media. To better understand the long term effect of future climate scenarios, especially at the higher latitudes, interaction of soil thermal state and hydrological dynamics is significant. Thus, a couple framework was developed to simulate interactive effects of soil thermal and hydrological dynamics. Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model was chosen as the parent code in this modeling framework. GSSHA (Downer et al. 2006) is a fully distributed, physics based model that includes the ability to simulate overland flow, infiltration, saturated groundwater flow, evapotranspiration (ET), snow accumulation and melting, as well as many other physical processes. Past coupling efforts, for example coupling of subsurface storm drainage and tile drain in GSSHA (Ogden et al. 2011; Pradhan et al. 2009) has demonstrated GSSHA ability to simulate important surface, subsurface runoff generation processes and to explicitly represent fully coupled hydrodynamics. In this present framework, the Geophysical Institute Permafrost Laboratory (GIPL) model (Jafarov et al. 2012; Marchenko et al. 2008) is incorporated into the GSSHA parent model. The GIPL model simulates soil temperature dynamics and the depth of seasonal freezing and thawing by numerically solving a 1D quasi-linear heat equation with phase change.

## 2 Purpose

The purpose of this report is to describe the development of the coupled framework to explicitly model the soil moisture effects of soil thermal conductivity and heat capacity and the resulting effects on hydrological dynamics. The report consists of the technical, theoretical, and conceptual details in coupling the GIPL permafrost model to the hydrologic model GSSHA. The effects of seasonal freezing and thawing on hydrological dynamics are demonstrated by applying the coupled system to simplified test cases.

This document is an addendum to the original *GSSHA*'s User Manual (Downer and Ogden 2006) as it describes the details for developments after the user's manual was completed. Additional information on *GSSHA* can be found in the *GSSHA*'s User's manual, and the GSSHA wiki ([http://www.gsshawiki.com/Gridded\\_Surface\\_Subsurface\\_Hydrologic\\_Analysis](http://www.gsshawiki.com/Gridded_Surface_Subsurface_Hydrologic_Analysis)).

### **3 GIPL Coupling in GSSHA**

The basis of GSSHA is a two-dimensional (2D) uniform grid used for both surface and subsurface computations. Point computations, infiltration, ET, etc., are performed within a grid cell and the point responses are integrated to get the system response, overland flow, lateral groundwater flow.

GIPL is an implicit, finite-difference, numerical model which solves the one dimensional (1D) non-linear heat equation with phase change. The process of soil freezing/thawing is treated in accordance with relationships between the soil unfrozen water content and temperature. A special enthalpy formulation of the energy conservation law makes it possible to use a relatively coarse vertical resolution without loss of latent heat effects in the phase transition zone. The mathematical description section gives more detailed information on the enthalpy method. In the 2D grid, the soil thermal state provided by GIPL is a point process, and is solved for each cell in the 2D grid.

The spatial variability of land-surface and hydrodynamic parameters, including subsurface soil moisture state, are included in the GSSHA model, and made available to GIPL during simulation, Figure 1. GIPL uses these values to update the thermal state of the soil and passes this back to GSSHA. GSSHA uses the thermal state of the soil to determine whether the soils are frozen or unfrozen. This information is used to adjust saturation levels, hydraulic conductivities, and saturated groundwater media thickness used in water flow computations. These computations produce updated values of groundwater level and soil saturation that are then used in the GIPL model to produce new thermal state profiles in each grid cell. This change of information continues for the duration of the simulation, as depicted in Figure 2.

#### **3.1 GIPL Mathematical Model**

The GIPL numerical model solves the Stefan problem (Alexiades and Solomon 1993, Verdi 1994) of phase change which is the problem of thawing or freezing via conduction of heat. The enthalpy formulation is used in the solution of Stefan problem in GIPL. The core of the GIPL numerical model is based on the 1D, vertical, quasi-linear heat conductive equation (Sergueev et al. 2003):

Figure 1 GIPL as a permafrost component in GSSHA

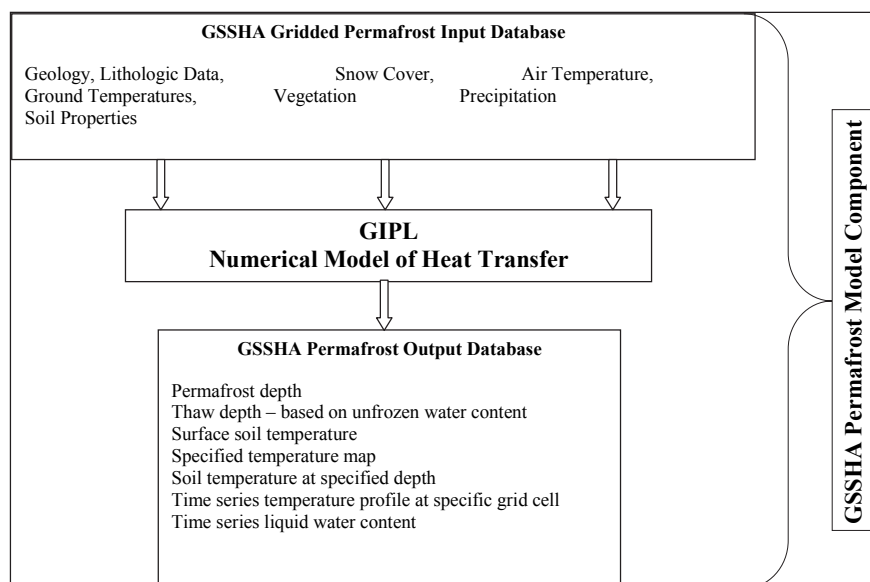
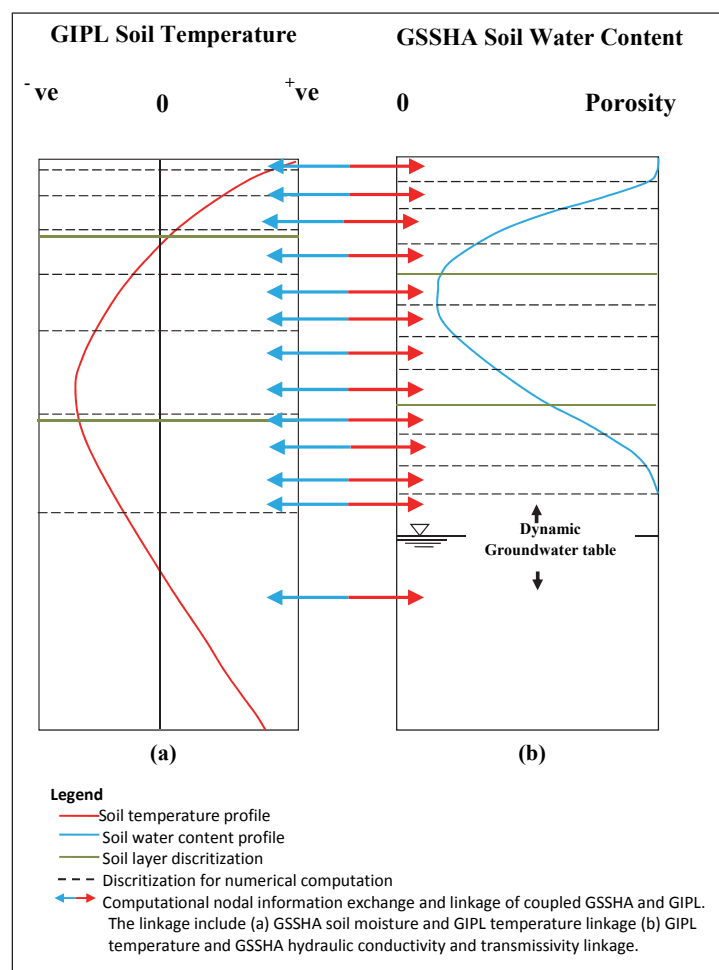


Figure 2 Schematic of GSSHA GIPL coupling/linkage.



$$\frac{\partial H(x,t)}{\partial \tau} = \nabla \cdot (k(x,t) \nabla t(x,\tau)) \quad (1)$$

where  $x$  is a vertical spatial variable which ranges between  $x_u$ , upper depth of the computational unit, and  $x_L$ , lower depth of the computational unit.  $t$  is temperature and  $\tau$  is time. The term  $k(x,t)$  is a thermal conductivity ( $\text{Wm}^{-1}\text{K}^{-1}$ );  $H(x,t)$  is an enthalpy function.

$$H(x,t) = \int_0^t C(x,s) ds + L\theta(x,t) \quad (2)$$

where  $C(x,s)$  is volumetric heat capacity ( $\text{MJm}^{-3}\text{K}^{-1}$ ),  $\theta(x,t)$  is volumetric unfrozen water content (%) and  $L$  is the volumetric latent heat of freeze/thaw ( $\text{MJm}^{-3}$ ). Equation 1 requires boundary and initial conditions. The upper part of the domain corresponds to the air layer which is at two meters height above the land surface. The fictitious domain formulation (Marchuk et al. 1986) allows embedding seasonal snow layer into the current air layer. The Dirichlet-type boundary condition is used as an upper boundary condition

$$t(x_u, \tau) = t_{\text{air}} \quad (3)$$

where  $t_{\text{air}}$  is a daily averaged air temperature. The geothermal gradient is set at the lower boundary:

$$\frac{\partial t(x_e, \tau)}{\partial x} = g \quad (4)$$

where  $g$  is geothermal gradient, a small constant ( $\text{Km}^{-1}$ ). For the initial temperature distribution, an appropriate ground temperature profile based on the point location is used.

$$t(x, \tau_0) = t_0(x) \quad (5)$$

The formula for unfrozen water content  $\theta(x,t)$  is based on empirical experiments and has the following form:

$$\theta(x,t) = \eta(x) \begin{cases} 1, & t \geq t_* \\ a|c-t|^{-b}, & t < t_* \end{cases} \quad (6)$$

Parameters  $a$  and  $b$  are dimensionless positive constants (Lovell 1957),  $c$  is freezing temperature, while  $\eta(x)$  is a volumetric soil moisture content. The constant  $t_*$  is a freezing point depression, the temperature at which ice begins to form in the soil, so that there is no ice if  $t > t_*$ . The unfrozen water content  $\theta(x, t)$  varies with depth, and time, and is dependent on soil type and hydrologic forcing. The discretized form of Equation 1 can be found in Sergueev et al. (2003) and Marchenko et al. (2008). A detailed mathematical description of the model and numerical solution methods can be found in Nicolsky et al. (2007).

Required input data include climate data, snow cover, soil thermal properties, lithological data, and vegetative cover. The main purpose of the model is to generate a spatial and temporal dataset of permafrost distribution and ground temperature dynamics as well as the active layer thickness which are useful in a wide range of hydrologic, ecological, climatologic, and socioeconomic assessments in cold regions.

## 3.2 GSSHA Subsurface Processes

### 3.2.1 Unsaturated Zone Model

In the GSSHA formulation as linked to GIPL, a 1D, vertical, unsaturated model rest atop a 2D, lateral, saturated groundwater flow model, as described below. GIPL is linked to GSSHA in both of these domains.

While various representations of the unsaturated zone are available in GSSHA, GIPL is linked in GSSHA in the unsaturated zone with the Richards' Equation (Richards 1931). The Richards' Equation is a general solution of saturated/unsaturated water movement and soil moisture and as implemented in GSSHA can be used to calculate runoff resulting from a variety of conditions, including infiltration excess and saturation excess mechanisms, which can occur simultaneously in different areas of a watershed. For Richards' Equation there is no requirement that the runoff production mechanism be known a priori or limited to one type. The GSSHA model uses a one-dimensional finite-difference solution of Richards' Equation to simulate the unsaturated zone. In GSSHA, the unsaturated zone is linked to a two-dimensional finite-difference representation of saturated groundwater flow (Downer 2002; Downer and Ogden 2004). The groundwater solution is fully coupled to surface flows using a 1D implicit finite difference solution of equation. The vadose zone controls the flux of water between the land surface and groundwater and partitions

rainfall into runoff, infiltration, groundwater recharge and ET. In GSSHA the unsaturated zone below each overland flow cell is simulated using the one-dimensional (vertical direction) head-based form of Richards' Equation

$$C_m(\psi) \frac{\partial \psi}{\partial \tau} - \frac{\partial}{\partial z} \left[ K_{soil}(\psi) \left( \frac{\partial \psi}{\partial z} - 1 \right) \right] - W = 0 \quad (7)$$

where  $C_m$  is the specific moisture capacity,  $\psi$  is the soil capillary head (cm),  $z$  is the vertical coordinate (cm) (downward positive),  $\tau$  is time (h),  $K_{soil}(\psi)$  (cm) is the effective hydraulic conductivity and  $W$  is a flux term added for sources and sinks (cm h<sup>-1</sup>), such as ET and infiltration. The head-based form is valid in both saturated and unsaturated conditions (Haverkamp et al. 1977).

In GSSHA the soil column is subdivided into discrete cells and Richards' Equation is solved using a cell-centered implicit finite-difference numerical algorithm. The solution scheme is central-difference in space and forward difference in time and is thus second-order accurate in space, first-order accurate in time. Flux updating is performed to ensure mass balance for the head based formulation.

Variables  $K_{soil}$  and  $C_m$  from Equation (7) are non-linear on the water content of each cell. Unless field data are available, the Brooks and Corey (1964) equations, as extended by Huston and Cass (1987), are used to calculate  $K_{soil}$  and  $C_m$  based on the water content of the cell. One exception occurs when there are saturated cells in the soil column.

### 3.2.2 Saturated Groundwater Model

In GSSHA, the 2D lateral free surface water flow equation, Equation 8, describes the movement of water in the saturated groundwater zone. The controlling equation, as developed by Pinder and Bredehoeft (1968):

$$\frac{\partial}{\partial x} \left( T_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial x} \left( T_{xy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial y} \left( T_{yx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( T_{yy} \frac{\partial h}{\partial y} \right) = S \frac{\partial h}{\partial \tau} + W(x, y, \tau) \quad (8)$$

where  $T$  is the transmissivity (m<sup>2</sup> s<sup>-1</sup>),  $h$  is the hydraulic head (m),  $S$  is the storage term (dimensionless), and  $W$  is the flux term for sources and sinks (m s<sup>-1</sup>). It is assumed that off diagonal terms are not important, and that transmissivity can be expressed as the product of the hydraulic conductivity

of the media ( $K_{soil}$ ) and the depth of the saturated media ( $b$ ). Substituting surface water elevation ( $E_{ws} = h + \text{datum}$ ) for head, the free surface problem can be described as (Downer 2002)

$$\frac{\partial}{\partial x} \left( K_{xx} b \frac{\partial E_{ws}}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_{yy} b \frac{\partial E_{ws}}{\partial y} \right) = S \frac{\partial E_{ws}}{\partial \tau} + W(x, y, \tau) \quad (9)$$

This equation is solved using a five point implicit finite difference scheme. Solution is by linear successive over relaxation (LSOR) with Picard iterations on both  $T$  (from  $T = Kb$ ) and  $S$  (Downer 2002).

### 3.3 Coupling GIPL to GSSHA

The GIPL model is a standalone permafrost model that is used to compute a one-dimensional (vertical) soil temperature profile over time using static values of soil moisture at daily intervals. As implemented in GSSHA, GIPL is a subroutine that is used to compute a profile of soil temperature in every 2D grid cell, including time varying soil moisture and groundwater levels at varying time intervals, Figure 2. To accomplish this result several tasks were performed:

1. The original Geophysical Institute Permafrost Lab (GIPL) permafrost model was coded in FORTRAN. This FORTRAN source code was converted to stand alone C/C++ source code.
2. Originally, GIPL parameters were uni-dimensional in the soil's vertical profile but are lumped in the horizontal spatial extent of application. Significant effort was expended to make all the GIPL state variables and parameters distributed as grid based or permafrost soil type based before merging the C/C++ version of GIPL into GSSHA. Thus, the uni-dimensional limitations of GIPL are enhanced into multi-dimensional distributed applicability in GSSHA distributed modeling framework.
3. Originally, the GIPL numerical model of heat transport used daily or larger time-steps. As implemented in GSSHA, GIPL can have any time-step, as specified by the user. The default time-step is the infiltration time-step, which is on the orders of seconds or minutes.
4. Several thermo-hydrodynamic formulations and modeling concepts are implemented to link and exchange the information in GIPL and GSSHA, as described in Section 3.3.1

### 3.3.1 Linking GIPL and GSSHA Computational Nodes

In GSSHA, the unsaturated zone is subdivided into computation nodes that cover the time varying unsaturated zone, which rest on top of the saturated groundwater. The unsaturated zone is divided into four regions, corresponding to the A, B, and C soil horizons, as well as the groundwater media. The saturated groundwater computation is in 2D lateral, so there is no distribution in the vertical direction in the saturated zone. The location of the water table may be anywhere from or above, the land surface, to hundreds of meters below the soil surface. In GIPL, the soil column extends down to where the lower boundary condition is considered valid, Equation (4), very deep within the permafrost region. This may extend 1000 or more meters below the land surface. Because of the differences in domains and requirements for solution, in the coupled framework, the GIPL computational nodes are independent in terms of location of the GSSHA infiltration scheme computational nodes. Thus, a user of the permafrost model in GSSHA does not need to spend time matching the vertical discretization in GIPL and GSSHA infiltration numerical schemes. The linkage of computational nodal discretized information from GIPL to GSSHA and vice-versa is shown in Figure 2.

### 3.3.2 Linking GIPL Soil Thermodynamics with GSSHA Soil Moisture Hydrodynamics

The main information being passed during a GSSHA/GIPL coupled simulation is that GSSHA provides updated soil moisture profiles to GIPL, which is used to adjust the thermal capacity of the soil, and that GIPL provides updated soil temperatures to GSSHA, which is used to adjust the hydraulic conductivity of the soil, both vertically and laterally. The infiltration time step with updated soil moisture of GSSHA is used to update the soil temperature profile during a GIPL time step. The linkage of GSSHA soil moisture update to GIPL thermal update is shown in Figure 2.

### 3.3.3 Linking GIPL Soil Temperature and GSSHA Hydraulic Conductivity

In the unsaturated zone, the temperature effects are accounted for by adjusting the value of relative saturation ( $S_E$ ) and using that adjusted value to adjust the vertical hydraulic conductivity of the soil, based on temperature and saturation.

### 3.3.3.1 Estimation of the Relative Saturation:

The relative fraction of liquid water of the total soil moisture,  $S_E$  is defined as follows (Schulla 2012):

$$S_E = \left( \frac{1}{1 + (\alpha |1.22t|)^n} \right)^m \text{ for } t \leq 0^\circ\text{C} \quad (10)$$

where  $n$ ,  $m$ , and  $\alpha$  are the Van-Genuchten-Parameters as used in the Richards Equation;  $t$  is soil temperature in  $^\circ\text{C}$ . For temperatures above  $0^\circ\text{C}$ ,  $S_E$  is always 1; whereas for temperatures below  $-10^\circ\text{C}$  the value of  $S_E$  is assumed to be 0. The latter assumption is to reduce computational burden. Fine soils may still contain liquid water below  $-10^\circ\text{C}$ , but the fraction is negligible to any thermal and hydraulic transport process at the timescales of model applications (Schulla 2012).

### 3.3.3.2 Linking GIPL Soil Profile Temperatures and GSSHA Effective Hydraulic Conductivity:

The effect of reduced effective saturation in the soil due to freezing is reduced hydraulic conductivity. An effective hydraulic conductivity is computed for the entire soil matrix, including both the unfrozen and frozen fractions.

In the unfrozen portion of the soil an exponential response in effective hydraulic has been measured for freezing/thawing mineral and organic soils (Zhang et al. 2010). Accordingly, the exponential function is applied to calculate the effective hydraulic conductivity where the hydraulic conductivity  $K$  at a given temperature ( $t$ ) is a function of hydraulic conductivity of the unfrozen soil and the effective saturation  $S_E$  is as follows:

$$K_{soil}(t) = e^{S_E} \ln(K_t(\Theta)) + (1 - S_E)K_f \quad (11)$$

where  $K_{soil}(t)$  is the effective hydraulic conductivity in m/s;  $K_t$  is the hydraulic conductivity for  $S_E = 1$  and  $K_f$  is the frozen hydraulic conductivity ( $S_E = 0$ ). In practice, the contribution from the frozen portion of the soil,  $(1 - S_E)K_f$  is quite small and is often neglected. The linkage of GIPL thermal nodal information and GSSHA hydraulic conductivity nodal information is shown in Figure 2.

### 3.3.4 Linking Soil Heat Transfer Effect on Effective Groundwater Transmissivity

As described in Section 3.2.2, the transmissivity ( $T$ ) of the saturated media is the product of the lateral hydraulic conductivity ( $K$ ) and the thickness of the saturated media ( $b$ ). As GIPL provides temperatures along the entire soil profile, including both saturated and unsaturated (see Section 3.2.1) zones and the soil profile representations in GIPL and GSSHA are also linked (see Section 3.3.1) it is possible to determine what portions of the saturated zone are frozen, and which are not. Since the representation of the saturated groundwater media in GSSHA is a 2D lateral free surface equation (see Section 3.2.2) the frozen layers cannot be explicitly represented as such in the GSSHA model, but the saturated thickness (the depth of water flowing in an unsaturated flow cell) can be adjusted. In the coupled framework, the thickness of the effective saturated media,  $b$ , is computed by identifying the unfrozen sections of the soil profile and accumulating those unfrozen layers. This effective saturated thickness is used to compute  $T$  in the GSSHA groundwater sub-routine while updating the groundwater heads.

The depth of the unfrozen saturated media in GSSHA is determined by searching the GIPL nodes corresponding to the saturated media depth. If the GIPL node is within the saturated media and is not frozen, the thickness of that node is added to the saturated media depth. The search for frozen temperatures in the GIPL computational nodes is made proceeding from the top of the soil layer to the deepest computational node depth. If the nodal soil temperature is positive, the corresponding computation block/slice dimension is added to the saturated media depth. Otherwise the nodal soil temperature is negative, and the corresponding computation block/slice dimension is not added to the saturated media depth.

The applicable block/slice dimension is added to the saturated media thickness only if the corresponding GIPL nodal elevation is within the limit of GSSHA groundwater table elevation and the GSSHA aquifer bottom elevation.

In this top-to-bottom approach where ' $j$ ' is a GIPL node number, if the node above or below, the ' $j-1$ ' nodal temperature is frozen and the ' $j$ ' nodal temperature is unfrozen, the thickness of the saturated media is defined as the interpolated unfrozen depth between the frozen node and unfrozen node. This avoids the overestimation of the effective saturated depth.

Once the effective saturation depth is calculated, local/grid based GSSHA groundwater transmissivity is defined as the following:

$$T = K_{\text{groundwater}} * B_{\text{effective}} \quad (12)$$

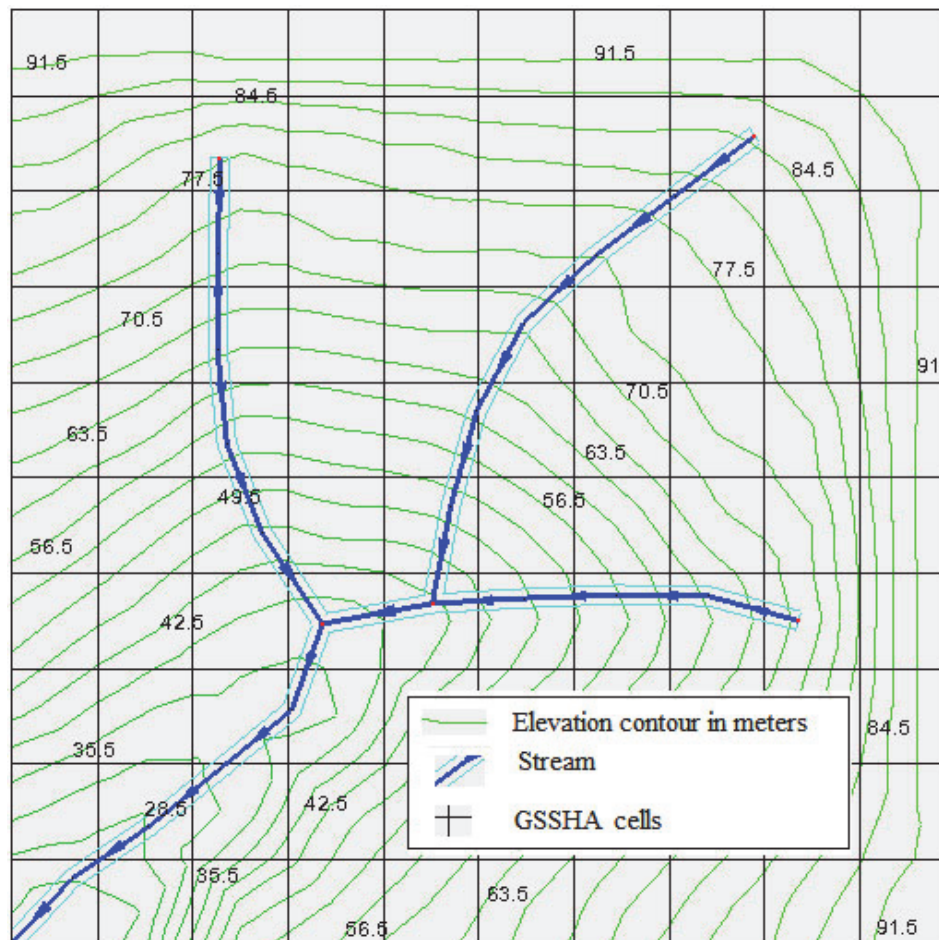
## 4 Test Cases

The test case example in this section illustrates modeling a permafrost active area with GIPL coupled in GSSHA. The simplified example is conceptual but the permafrost parametric values represent Alaskan woodland and tundra ecosystem sites in permafrost active regions. This example project includes surface subsurface runoff where infiltration and groundwater components are turned on. The soil moisture and soil physical state is defined by the Richards Equation.

### 4.1 Example Model

Figure 3 shows the test case example model having 10×10 building blocks.

Figure 3. A test case 10×10 example project of coupled GSSHA and GIPL, where the permafrost parametric values represent woodland and tundra ecosystem sites in permafrost active Alaskan regions.



#### 4.1.1 Permafrost Boundary

The entire test case is regarded as a permafrost active zone. The permafrost soil properties as defined in Table 1 are from an Alaskan woodland and tundra ecosystem permafrost site.

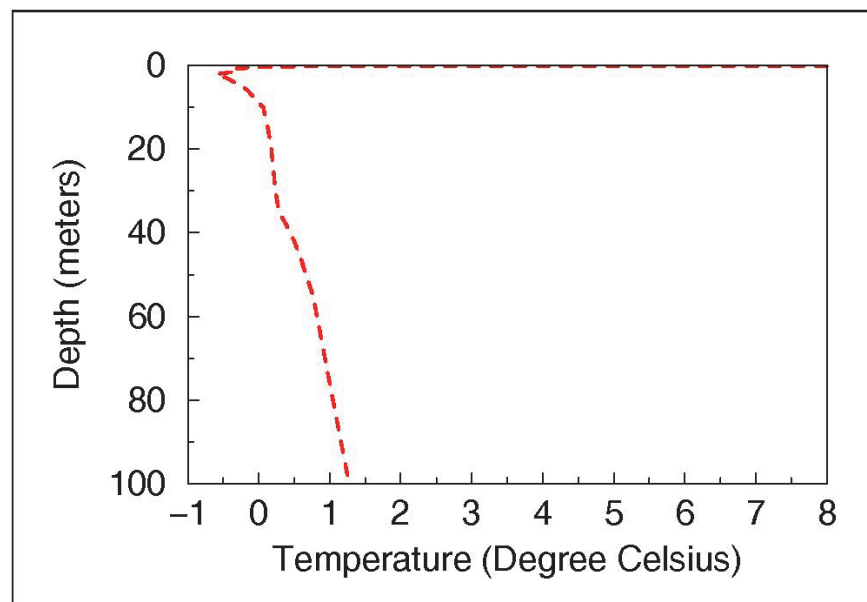
Table 1. Permafrost parametric value.

Description	unit	value
Volumetric soil water content	Fraction of 1	0.87
Volume of unfrozen water	Fraction of 1	0.11
A-parameter of unfrozen water	-	0.034
B parameter of unfrozen water	-	-0.32
C parameter of unfrozen water	-	0.0
Soil thermal conductivity thawed	$W\ m^{-1}\ K^{-1}$	0.0201
Soil thermal conductivity frozen	$W\ m^{-1}\ K^{-1}$	0.0551
Volumetric heat capacity	$Jm^{-1}m^{-1}m^{-1}K^{-1}$	2800

#### 4.1.2 Initial Condition

Figure 4 shows the initial temperature condition which is from an Alaskan woodland and tundra permafrost location.

Figure 4. Soil temperature profile as an initial condition for the thermodynamics numerical simulation.



## 4.2 Model Results

Figure 5 shows simulated soil temperature profile extracted from the time series.

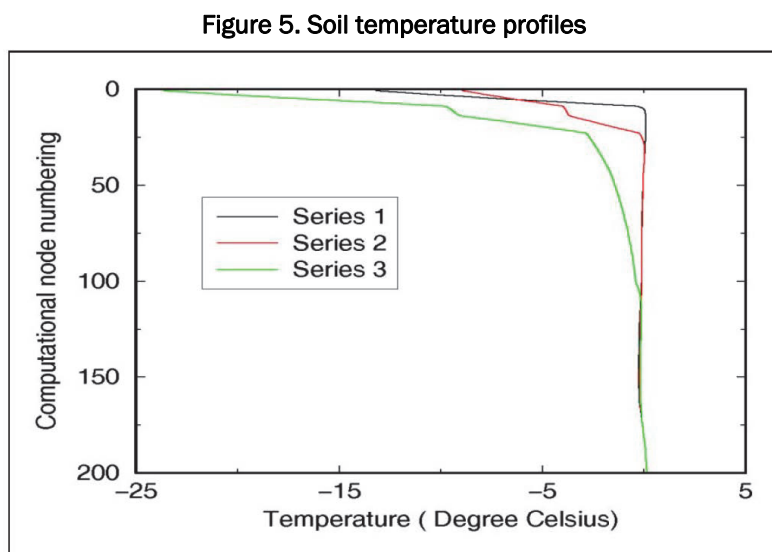
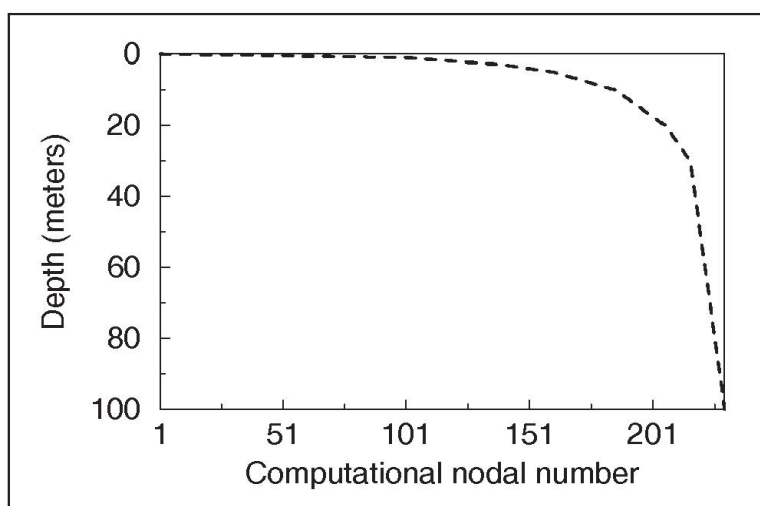


Figure 5 shows the vertical soil temperature at computational nodal points and Figure 6 shows the corresponding depths for the nodal points.

**Figure 6. Depth information of the computational nodal number.**



Permafrost is separated from the atmosphere by a boundary layer consisting of the active layer. The active layer transmits heat to and from permafrost. The top of permafrost is at the base of the active layer. An active layer is the soil column that experiences normal freezing and thawing during the seasons. Figure 5 shows the freeze cycle of the active layer. In

Figure 5, the temperature profile in the active layer shows decreasing values while moving from one time series to another. This decrease in the temperature values lead to decrease in free water content in the frozen soil thereby decreasing the hydraulic conductivity of the soil. Computational nodes were closer in the active layer which is shown in Figure 6.

Figure 7 shows the soil temperature at various depths. Figure 7 shows that the air temperature has the most significant influence in the near surface soil layer. As the soil layer depth increases, air temperature influence in soil thermo-dynamics is diminished along with the increase in the time lag influence.

Figure 7. Time-series of temperature at various depths.

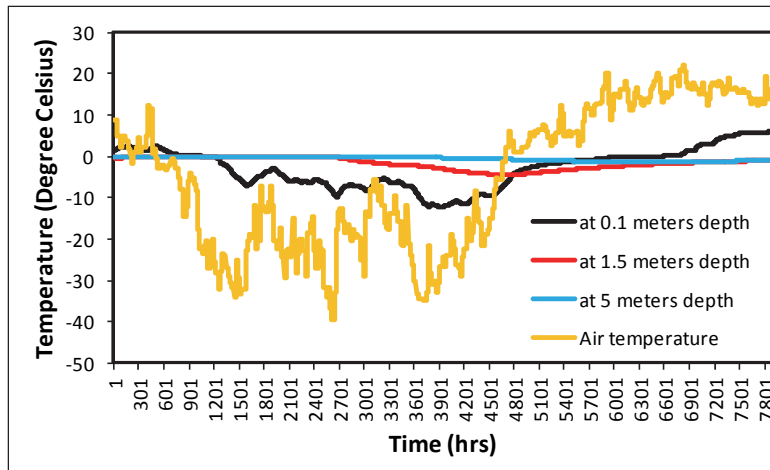


Figure 8 shows the change in effective hydraulic conductivity due to frozen soil condition. The effective hydraulic conductivity decreases with increasing fraction of ice, i.e. a decreasing  $S_E$  value in Equation (10) and Equation (11). The effective hydraulic conductivity changes with several orders of magnitude as the soil freezes/thaws which is defined by Equation (11) with an exponential response in effective hydraulic conductivity. Figure 8 shows the decrease in soil effective hydraulic conductivity from  $1 \text{ cm hr}^{-1}$  to almost zero when the active layer soil column started to freeze. This simulation result of the change in effective hydraulic conductivity due to soil freezing condition agrees with the fact that the effective hydraulic conductivity changes by several orders of magnitude as the soil freezes/thaws.

Figure 8. Hydraulic conductivity under active permafrost soil layer.

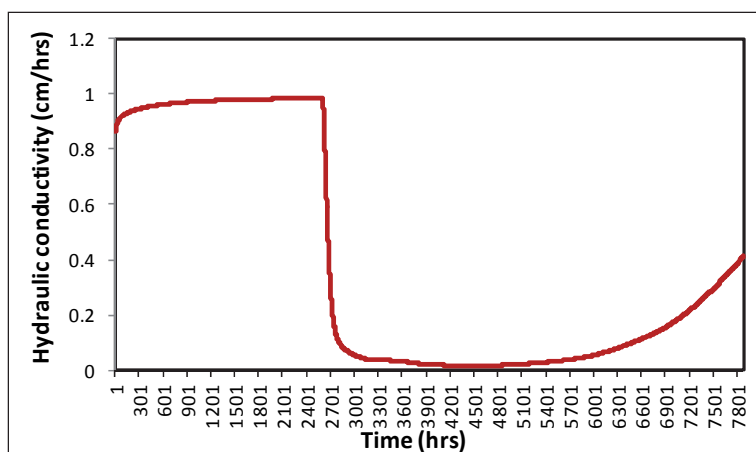


Figure 9 shows the comparison of GSSHA simulated discharge with and without the permafrost model.

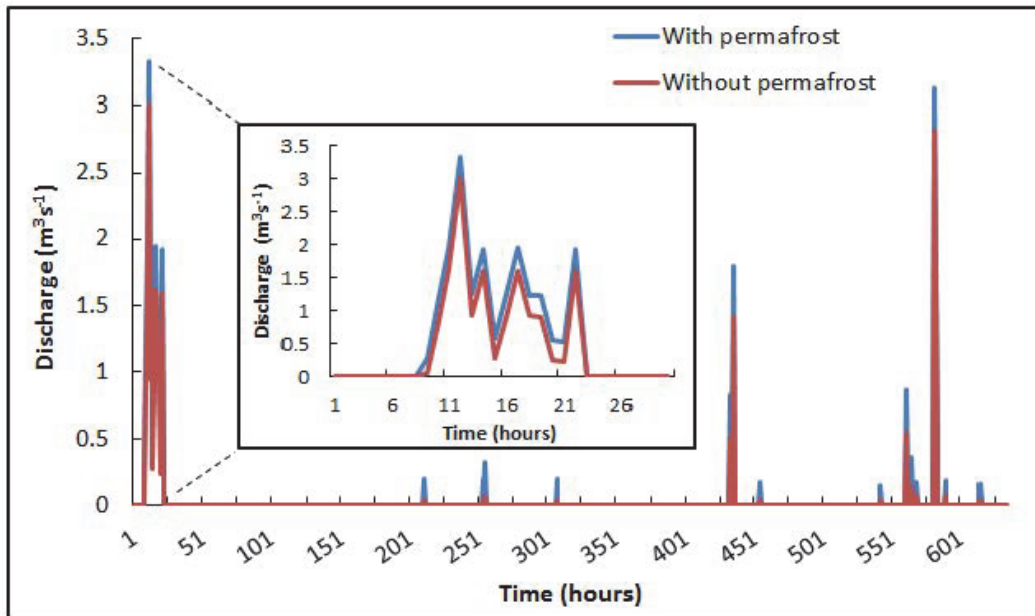
### 4.3 Discussion

Stream response to storms differs for permafrost-free and permafrost-affected slopes. Stream flow from watersheds underlain with a large proportion of permafrost responds rapidly to precipitation, with rapid rising and falling limbs of storm hydrographs (Quinton and Carey 2008). The simulation result with permafrost, shown in Figure 9, had rapid response to the precipitation event with increased peaks than that without the permafrost. This verified that the model produced desired and expected output.

In contrast, for streams with little or no permafrost, precipitation can percolate into soil layers resulting in enhanced connectivity between the surface and ground water storage regimes and more soil pore water storage. Because of this enhanced connectivity and soil pore water storage capacity, Figure 9 shows reduced peak discharge and runoff volume for the permafrost-free simulation in comparison to the result with permafrost.

All those simulation results presented in Section 4.2 show that GSSHA coupled with GIPL could serve as a valuable tool for long-term simulation and prediction of interactive effects of frozen soil hydrological dynamics in permafrost regions.

Figure 9. Hydrograph with and without active permafrost.



## 5 Summary

A coupled framework was developed for simulating the interaction between soil temperature, including permafrost, and hydrology, by incorporating the soil temperature and permafrost model GIPL into the distributed, physics based hydrologic model GSSHA. The report describes the numerical considerations in linking the GIPL thermo-dynamic model into GSSHA's hydrodynamic modeling framework. GSSHA hydrodynamics include soil moisture saturation feedback in the vadose zone and the corresponding soil ice content effects on hydraulic conductivity and transmissivity.

The coupled model was demonstrated on a contrived watershed, around a previous GIPL test site. The coupled simulation results show that the effect of soil thermal properties obtained from GIPL play a significant role in the GSSHA hydrological dynamics and vice versa.

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